

Executive Summary

Introduction and Purpose

Concerns have been raised regarding whether homeowners use windows, doors, exhaust fans, and other mechanical ventilation devices enough to remove indoor air contaminants and excess moisture. Building practices and building standards for energy efficiency have led to more tightly sealed homes that rely on occupants to open windows for ventilation. However, there is very little information on current ventilation practices, indoor air quality, or indoor air contaminant sources in homes. This study provides, for the first time, accurate and current statewide information on ventilation and indoor air quality in new California homes.

A mail survey conducted in 2005 on occupants' use of windows and mechanical ventilation equipment in 1,515 new single-family homes in California confirmed that many homeowners never use their windows for ventilation. From this mail survey, a concern emerged that the current California residential building code allowance for ventilation to be provided merely through openable windows may not be sufficient to enable new homes to receive adequate ventilation to control indoor air contaminants to acceptable levels.

As a follow-up to the mail survey, a large field study was then conducted to measure window and mechanical ventilation system use, outdoor air ventilation rates, sources and concentrations of indoor air contaminants, and occupant perceptions. Data on indoor air quality and household ventilation systems and practices were obtained from multiple seasons and regions of the state. Measured levels of ventilation and indoor air quality were compared to current guidelines and standards. These data will help characterize the full range of indoor air contaminant exposure in such homes. Information on the use of windows, fans, and central systems collected in this field study will help establish realistic values for developing California standards for building energy efficiency.

The Energy Commission used these study results to revise the state's 2008 Residential Building Energy Efficiency standards to require mechanical ventilation to provide more healthful homes in California. The study results will improve the California Air Resource Board's ability to identify current sources of indoor air contaminants, to assess Californians' current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.

Methods

The field study design involved recruitment of single-family detached Californian homes built between 2002 and 2004, using the University of California at Berkeley mail survey database as well as some supplementary recruitment. The homes were occupied by owners for at least one year before testing occurred, and homes with occupants who smoked indoors were excluded. This field study involved 108 homes from Northern and Southern

California, including a subset of 26 homes with mechanical outdoor-air ventilation systems. Home age ranged from 1.7 years to 5.5 years. The field teams measured home ventilation and indoor contaminant source characteristics, including the amount of composite wood, indoor contaminant concentrations, the residents' ventilation practices, indoor air quality perceptions, and decision factors regarding ventilation and indoor air quality-related actions. Measurements of indoor and outdoor air quality and ventilation parameters were made in the summer and fall of 2007 and the winter of 2007–2008. Indoor air concentrations of 22 volatile organic compounds, formaldehyde, acetaldehyde, PM_{2.5} particulate matter, nitrogen dioxide, carbon monoxide, carbon dioxide, temperature, and relative humidity were measured over one 24-hour period. The outdoor air ventilation rates were determined concurrent with the air contaminant measurements using tracer gas measurements. In addition, the field teams measured the building envelope air leakage, garage-to-home air leakage, forced air unit duct leakage, window use, airflow rates, and fan system use. Twenty of the 108 homes were tested in both the summer and winter seasons; four homes were tested in the summer, fall, and winter; and four homes were tested over multiple days, including weekends.

Results and Discussion

The following summarizes the results and provides some of the key discussion points for each of the six study objectives.

Objective 1. Determine how residents use windows, doors, and mechanical ventilation devices such as exhaust fans and central heating and air-conditioning systems.

Occupant Use of Windows and Doors for Ventilation. In this field study, 32 percent of the homes did not use their windows during the 24-hour test day, and 15 percent of the homes did not use their windows during the entire preceding week (Table E1). Most of the homes with no window use were homes in the winter field session. The study concluded that a substantial percentage of homeowners never open their windows, especially in the winter, and confirms the seasonal results from the University of California at Berkeley mail survey and the previous California Air Resources Board-funded statewide survey of human activity patterns. Results from the mail survey indicate that many homeowners never open their windows or doors for ventilation as a result of their concerns for security/safety, noise, dust, and odors.

Table E1. Summary of window and door opening usage during the 24-hour Test Day and the preceding one week.

	Number of Homes Tested	Number of Homes with No Window/Door Usage	Percentage of Homes with No Window/Door Usage (%)
Test Day ^a	108	34	32
Preceding Week ^b	108	16	15
a) Test day usage was measured during the 24-hour air testing day. b) Preceding week usage was measured during the one week preceding the 24-hour air testing day.			

Occupant Use of Mechanical Outdoor Air Systems. For the two types of mechanical outdoor air systems encountered in the field study—ducted outdoor air systems and heat recovery ventilator systems—the median test day use was 2.5 hours for the ducted outdoor air systems (n=14) and 24 hours for heat recovery ventilator systems (n=8). These data indicate that the ducted outdoor air systems, which typically are operated intermittently and in conjunction with the forced air unit fan, operate for only a small portion of the day, while the heat recovery ventilator systems are typically operated continuously. To ensure adequate delivery of outdoor air to the home, ducted outdoor air systems should have a fan cyclers, so that even if the thermostat fan switch does not operate the forced air unit fan, the fan is automatically operated for a minimum time. Few of the homes in this study with operational ducted outdoor air systems (four of the 14 homes) had fan cyclers. Thus, to ensure adequate and energy efficient delivery of outdoor air to the home, ducted outdoor air systems should include a fan cyclers with fan cycle times and outdoor airflow rates set to provide sufficient outdoor air ventilation.

Occupant Use of Mechanical Nighttime Cooling Systems. For the two types of nighttime cooling systems found in the field study—whole house fan systems and forced air unit return air damper systems—the median test day use was 0.7 hours for whole house fan systems and 5.3 hours for return air damper systems. Use of these systems was confined primarily to the summer months, so the nighttime cooling systems were operated for relatively few hours each day, with the return air damper systems having longer operating times.

Occupant Use of Forced Air Unit Systems. The median test day use for forced air units was 1.1 hours; 32 percent of the homes had zero forced air unit use during the 24-hour test day, and 11 percent had zero use during the entire preceding week. This low operating time of the forced air unit fan limits the effectiveness of ducted outdoor air systems, which depend on the operation of the forced air unit fan, to deliver the required outdoor air.

Objective 2. Measure and characterize indoor air quality, ventilation, and the potential sources of indoor pollutants.

Forced Air Heating/Cooling System Duct Leakage. A total of 86 percent of the homes had duct leakage exceeding the California Title 24 maximum of 6 percent, demonstrating that new homes in California have relatively leaky ducts.

Home Building Envelope Air Leakage Area. The median ACH₅₀ (air changes per hour at 50 pascals) for the homes in this study was 4.8 air changes per hour, which compares to a median of 5.2 air changes per hour for a group of homes built since 1992 and 8.6 air changes per hour for a group of homes built before 1987. New Californian homes are generally being built tighter, but not exceptionally tight, like those found in colder climate regions.

Home-to-Garage Air Leakage. A total of 65 percent of the homes did not meet the American Lung Association guideline for a home-to-garage negative pressure of at least -49 pascals when the home is depressurized to -50 pascals with respect to the outdoors. In the three-home pilot study, tracer gas measurements indicated that between 4 percent and 11 percent of the garage sources entered the home. A substantial amount of air from attached garages, which often contain air contaminant sources such as vehicle fuel, exhaust fumes, gasoline-powered lawn equipment, solvents, oils, paints, and pesticides, can enter the home's indoor air.

Mechanically Supplied Outdoor Airflow Rates. Sixty-four percent of ducted outdoor air systems failed to meet the California Energy Commission's new 2008 Building Energy Efficiency Standards. The very low outdoor air exchange rates for the ducted outdoor air systems resulted from a combination of low outdoor airflow rates and short operating times. Heat recovery ventilator systems performed much better. All of the heat recovery ventilator systems met the new 2008 Building Energy Efficiency Standards. These results show that the heat recovery ventilator systems that we tested are a more effective outdoor air supply strategy than the ducted outdoor air systems.

The performance of the ducted outdoor air systems is poor because these systems (1) lacked controls (such as fan cyclers) to ensure adequate operating times of the forced air unit fan, and (2) lacked proper sizing and balancing of the outdoor air duct to ensure sufficient outdoor airflow rate into the system when the forced air unit fan was operated.

In addition, the performance of intermittent mechanical outdoor air systems (such as ducted outdoor air systems) is not equivalent to continuous systems (such as heat recovery ventilator systems) with respect to controlling the short-term exposures to indoor air contaminants, especially if the cycle times are long (for example, greater than two hours). The 2008 Building Energy Efficiency Standards, which were adopted after this study was completed, require a minimum operation time of 1 hour every 12 hours. During extended

outdoor air ventilation off-times, intermittent ventilation systems allow for air contaminants with indoor sources to increase substantially as compared to the increases that would occur with a continuous ventilation system. For some indoor air contaminants, such as those that cause irritation and/or odor, the effects are initiated by the immediate exposure to the indoor concentration rather than prolonged exposure to a concentration over a period of time. For such compounds, intermittent ventilation systems may not be sufficient for reducing indoor concentrations to acceptable levels.

Tracer Gas Measurements of Home Outdoor Air Exchange Rates. The median 24-hour outdoor air exchange rate measurement was 0.26 air changes per hour, with a range of 0.09 air changes per hour to 5.3 air changes per hour (Table E2). A total of 67 percent of the homes had outdoor air exchange rates below the minimum California Building Code requirement of 0.35 air changes per hour.

Table E2. Summary comparison of outdoor air exchange rate measurements and CBC 2001 minimum code requirements.

	Number of Homes Tested	Minimum Air Exchange Rate (ach)	Median Air Exchange Rate (ach)	Maximum Air Exchange Rate (ach)	CBC Code Requirement (ach)*	Percentage of Homes Below CBC Code Requirement (%)
24-Hour Measurement	106	0.09	0.26	5.3	0.35	67
* 2001 California Building Code, Appendix Chapter 12, Interior Environment, Division 1-Ventilation, Table A-12-A, Outdoor Air Requirements for Ventilation, Living Areas. Air changes per hour (California Building Code 2001).						

The relatively tight envelope construction, combined with the fact that many people never open their windows for ventilation, resulted in many homes with low outdoor air exchange rates.

Indoor Air Contaminant Concentrations. The only indoor air contaminants that exceeded recommended non-cancer and non-reproductive toxicity guidelines were formaldehyde and PM_{2.5} particulate matter. For formaldehyde, 98 percent of the homes exceeded the 2008 Chronic and 8-hour Reference Exposure Levels for irritant effects of 9 micrograms per cubic meter, 59 percent exceeded the 2005 California Air Resources Board's indoor air guideline for irritant effects of 33 micrograms per cubic meter, and 28 percent exceeded the 2008 Acute Reference Exposure Levels for irritant effects of 55 micrograms per cubic meter (Table E3). None of the homes exceeded the 2008 Reference Exposure Levels for acetaldehyde. For PM_{2.5}, only one home, with an indoor concentration of 36 micrograms per cubic meter, exceeded the U.S. Environmental Protection Agency's PM_{2.5} 24-hour ambient air quality standard of 35 micrograms per cubic meter.

Table E3. Summary comparison of indoor concentrations of formaldehyde, acetaldehyde, and indoor air contaminant guidelines.

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Compound	Number of Homes Tested	Minimum Concentration (µg/m ³)	Median Concentration (µg/m ³)	Maximum Concentration (µg/m ³)	Indoor Air Guideline (µg/m ³)	Percentage Above Indoor Air Guideline (%)
Formaldehyde	105	4.8	36	136	2 ^a	100
					9 ^b	98
					9 ^c	98
					33 ^d	59
					55 ^e	28
Acetaldehyde	105	1.9	20	102	4.5 ^a	93
					140 ^b	0
					300 ^c	0
					470 ^e	0
a) Proposition 65 No Significant Risk Level for carcinogens (OEHHA 2008a). b) Office of Environmental Health Hazard Assessment Chronic Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed. c) OEHHA 8-hour Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed. d) <i>Indoor Air Quality Pollution in California</i> (California Air Resources Board 2005). e) OEHHA Acute Reference Exposure Levels, 2008 (OEHHA 2008b). Adopted after study completed.						

Most new homes had indoor formaldehyde concentrations that exceeded recommended guidelines.

Volatile Organic Compound Proposition 65 Safe Harbor Levels. For each of the seven volatile organic compounds with No Significant Risk Levels for cancer, there were some homes that exceeded the No Significant Risk Levels concentration indoors. As summarized in Table E3 for formaldehyde and acetaldehyde, the percentages of homes exceeding the No Significant Risk Levels concentration were 100 percent and 93 percent, respectively. For the five other volatile organic compounds, the percentage of homes exceeding the No Significant Risk Levels concentration ranged from 8 percent for trichloromethane (chloroform) and tetrachloroethene to 63 percent for benzene.

For the two volatile organic compounds with Maximum Allowable Dose Levels for reproductive toxicity, only the benzene Maximum Allowable Dose Levels was exceeded. A total of 20 percent of the homes had indoor benzene concentrations that exceeded the calculated indoor Maximum Allowable Dose Levels concentration. Thus, a substantial percentage of new homes have indoor concentrations that exceed recommended guidelines for cancer and/or reproductive toxicity.

Potential Sources of Indoor Air Contaminants. The primary source of the indoor concentrations of formaldehyde and acetaldehyde, which were the two air contaminants that most frequently exceeded recommended guidelines, is believed to be composite wood products. While the research team was not able to determine the extent to which formaldehyde-based resins were used in the composite wood identified in the homes, formaldehyde-based resins are the most common resins used in the production of composite wood products. The composite wood identified in these homes include particleboard that was used in 99 percent of the kitchen and bathroom cabinetry, as well as many pieces of furniture. Other sources of composite wood include plywood and oriented strand board in walls, subfloors, and attics, and medium density fiberboard in baseboards, window shades, interior doors, and window/door trims.

Potential sources of some volatile organic compounds were identified for homes with elevated indoor volatile organic compound concentrations. The following potential sources of indoor air contaminants are suggested from a comparison of the occupant activity logs and house characteristics with the indoor contaminant concentrations and emission rates: 1,4-dichlorobenzene and naphthalene from mothballs, d-limonene from furniture polish and cleaning chemicals, 2-butoxyethanol from anti-bacterial wipes, toluene from air fresheners, and tetrachloroethene from dry cleaned clothes or drapes.

Objective 3. Determine occupant perceptions of, and satisfaction with, the indoor air quality in their homes.

A total of 28 percent of the households reported experiencing one or more of nine physical symptoms during the previous three weeks that they did not experience when they were away from the home. The three most frequently reported symptoms were nose/sinus congestion (19 percent), allergy symptoms (15 percent), and headache (13 percent). The three most frequently reported thermal comfort perceptions were “too cold” (19 percent), “too hot” (15 percent), and “too stagnant (not enough air movement)” (12 percent). Thus, a substantial percentage of occupants of new homes report experiencing physical symptoms or thermal discomfort.

Objective 4. Examine the relationships among home ventilation characteristics, measured and perceived indoor air quality, and house and household characteristics.

Statistical comparisons were conducted for indoor formaldehyde and acetaldehyde concentrations, outdoor air exchange rates, and window usage. Formaldehyde and acetaldehyde were selected for these analyses, as these were the two air contaminants that most frequently exceeded recommended indoor concentration guidelines. Because of the small number of homes in the sample groups and the important seasonal and house-specific differences, these comparisons should only be considered as suggestive of differences. Multivariate analyses need to be done to further establish any differences between the groups.

Formaldehyde concentrations were found to be significantly higher in the following group comparisons:

- Non-mechanically ventilated Northern California homes had higher formaldehyde concentrations than Southern California homes
- Ducted outdoor air homes had higher formaldehyde concentrations than homes without mechanical outdoor air ventilation systems
- Ducted outdoor air homes had higher formaldehyde concentrations than heat recovery ventilator homes

Acetaldehyde concentrations were found to be significantly higher in the following group comparisons:

- Ducted outdoor air homes had higher acetaldehyde concentrations than homes without mechanical outdoor air ventilation systems
- Ducted outdoor air homes had higher acetaldehyde concentrations than heat recovery ventilator homes

Window usage was found to be significantly higher in the following group comparisons:

- Summer homes had higher window usage than winter homes

Outdoor air exchange rates were found to be significantly higher in the following group comparisons:

- Heat recovery ventilator homes had higher outdoor air exchange rates than homes without mechanical outdoor air ventilation systems
- Heat recovery ventilator homes had higher outdoor air exchange rates than ducted outdoor air homes

Correlation analyses were also conducted for indoor formaldehyde and acetaldehyde concentrations with six home characteristics and four environmental conditions. For both formaldehyde and acetaldehyde concentrations, the outdoor air exchange rate was determined to have a significant inverse correlation. For formaldehyde concentrations, indoor air temperature was determined to have a significant correlation. These results indicate that as outdoor air exchange rates decrease or the indoor temperature increases, the indoor concentrations of formaldehyde increase.

Objective 5. Identify the incentives and barriers that influence people's use of windows, doors, and mechanical ventilation devices for adequate air exchange.

Of the homeowners with mechanical outdoor air systems (that is, ducted outdoor air or heat recovery ventilator systems, not nighttime cooling systems, evaporative cooling systems, or window fans):

- 78 percent stated that the operation of the system was explained to them when they bought or moved into the house
- 63 percent responded that they understood how the system works
- 83 percent stated that they felt that they understood how to operate the system properly

A total of 91 percent stated they chose the system because it came with the house, and the things they liked most about the system were: "Fresh air" (52 percent), "Quiet" (48 percent), and "Reduced concern about indoor air quality" (26 percent). The things they liked least about the system were: "Not effective" (32 percent), "Too drafty" (26 percent), and "Too noisy" (26 percent).

Objective 6. Identify the incentives and barriers related to people's purchases and practices that improve indoor air quality, such as the use of low-emitting building materials and improved air filters.

A total of 24 percent of the 105 respondents stated "none" in response to the question "What special measures or choices have you or the builder taken to improve the quality of the air in your home?" The four most frequent responses to improvements undertaken were: "Hard flooring instead of carpeting" (33 percent), "Carbon monoxide alarm" (28 percent), "High efficiency vacuum cleaner with special features such as filters to trap more particles" (27 percent), and "Upgrade my central air filter" (25 percent).

Conclusions

The following summarizes the main conclusions from this study of new single-family homes built in California in 2002–2004.

1. Many homeowners never open their windows or doors, especially in the winter months.
2. New homes in California are built relatively tight, such that outdoor air exchange rates through the building envelope can be very low (e.g., 0.1 air changes per hour).

3. In new homes with low outdoor air exchange rates, indoor concentrations of air contaminants with indoor sources, such as formaldehyde and some other volatile organic compounds, can become substantially elevated and exceed recommended exposure guidelines.
4. Ducted outdoor air mechanical outdoor air ventilation systems generally did not perform well as a result of the low outdoor airflow rates and short operating times. A total of 64 percent of ducted outdoor air systems failed to meet the American Society of Heating, Refrigerating and Air-Conditioning Engineers 62.2-2007 standard for residential ventilation, which is referenced in the Energy Commission's 2008 Building Energy Efficiency Standards.
5. Heat recovery ventilator mechanical outdoor air ventilation systems performed much better than ducted outdoor air systems. All heat recovery ventilator systems met the California Energy Commission's new 2008 Building Energy Efficiency Standards.

Recommendations

1. Consideration should be given to installing mechanical outdoor air ventilation systems in new single-family residences to provide a dependable and continuous supply of outdoor air to the residence for the purpose of controlling indoor air contaminants.
2. Consideration should be given to regulating the emissions of air contaminants from building materials, such as the 2007 California Air Resources Board regulation to limit formaldehyde emissions from composite wood products.
3. Given the relatively high frequency of indoor formaldehyde concentrations that exceeded recommended exposure guidelines, and the fact that formaldehyde is a known human carcinogen, consideration should be given to conducting studies focused on quantifying the emission rates of formaldehyde from all potential indoor sources (such as building materials, furnishings, consumer products, and others). Based on this research, regulations should be developed to reduce indoor formaldehyde emissions.
4. Outreach to public and professional groups should be increased regarding the need to reduce indoor formaldehyde concentrations in existing homes by sealing exposed composite wood surfaces, selecting low-emission furniture, improving outdoor air ventilation in the home, and controlling indoor humidity.
5. Multivariate analyses of the data collected in this study should be conducted to further develop the understanding of the relationships between indoor air

contaminant concentrations, indoor sources, ventilation, season, and other major sources of variance.

6. A statewide population-weighted assessment from the data collected in this field study should be performed to better understand the air contaminant source and ventilation characteristics of new homes.
7. Additional studies of indoor air quality and ventilation with diurnal wind speed and temperature swings should be conducted to examine the significance of nighttime cooling by natural or mechanical means.
8. Further studies in additional homes with mechanical outdoor air ventilation systems should be conducted to confirm the findings identified in this study and with consideration for other building factors. Both installation and field performance of the mechanical outdoor air ventilation systems should be evaluated.
9. Revision of the intermittent ventilation effectiveness factors in the 2008 Building Energy Efficiency Standards and the Energy Commission's companion Residential Compliance Manual should be considered, to provide intermittent ventilation that results in indoor air quality that is comparable to that provided by continuous ventilation systems.
10. Research should be conducted on exhaust-only ventilation systems, which were not encountered in this study but may be used widely in the future.
11. Home builders should be educated about the importance of conveying to homeowners the need for outdoor air ventilation in homes, how the ventilation systems operate, and the importance of designing systems that are easy for homeowners to maintain. In addition, consider creating an easy-to-read short fact sheet that can be distributed to the public regarding residential ventilation systems and the importance of the operation and maintenance of these systems to indoor air quality.
12. Research should be conducted to investigate residential exposures to ozone-initiated reaction products, such as formaldehyde and other aldehydes and ultrafine particles, that are formed when ozone reacts with contaminants such as d-limonene, which is emitted by many air freshener and cleaning products as well as some orange oil termite treatments. This project's database contains important information for such research, including d-limonene concentrations, outdoor air exchange rates, air cleaners that generate ozone, and formaldehyde and other aldehyde concentrations.

Benefits to California

This was the first large field study of window use, outdoor air ventilation rates, and indoor air contaminants in new California homes. The data from this study were immediately useful for the California Energy Commission in guiding the development of building design standards that require mechanical ventilation to protect indoor air quality and comfort in California homes and for the California Air Resources Board to improve exposure assessments of indoor and outdoor air contaminants. In particular, the Energy Commission used the study results as a scientific basis to revise the State's building energy efficiency standards to provide more healthful, energy-efficient homes in California. The study results will also improve California Air Resources Board's ability to identify current sources of indoor air contaminants, to assess Californians' current exposure to measured toxic air contaminants, and to recommend effective strategies for reducing indoor air pollution.